On the responses to solar X-ray flare and coronal mass ejection in the ionospheres of Mars and Earth

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[1] We have used Mars Global Surveyor (MGS) observations for the period 12 to 18 May 2005 to address the effect of X-ray flare and Coronal Mass Ejection (CME) on the Total Electron Content (TEC) of the E region ionosphere of Mars during a violent solar event that occurred on 13 May. Modeling of E region TEC was also carried out for the time of the flare using the observed X-ray flux. We report that the solar flare caused enhancements in the TEC of Mars by factors of 6 to 10. A response was also observed in the E region plasma frequency of the Earth's ionosphere at nearly same time as the MGS observations. Our results suggest that sporadic E layer plasma frequency and TEC can increase by factors of 3 to 6 during the arrival of a CME at both Earth and Mars. **Citation:** Haider, S. A., M. A. Abdu, I. S. Batista, J. H. Sobral, E. Kallio, W. C. Maguire, and M. I. Verigin (2009), On the responses to solar X-ray flare and coronal mass ejection in the ionospheres of Mars and Earth, *Geophys. Res. Lett.*, *36*, L13104, doi:10.1029/2009GL038694.

1. Introduction

[2] The effect of solar flare and CME is a key problem in all planetary atmospheres [*Mendillo and Withers*, 2008; *Bhardwaj et al.*, 2005; *Prange et al.*, 2004]. We have observed this effect in the ionospheres of Mars and Earth during a violent solar event that occurred on 13 May 2005 at 17:00 UT. At this time the emission at 10 cm wavelengths was more than 80 times higher than the normal background noise of the Sun. The Sun was active over ~3 hours. This flare was observed by the Geostationary Operational Environmental Satellite (GOES) 12 at two wavelength bands from 0.5–4 Å and 1–8 Å [*Bornmann et al.*, 1996]. Figure 1a represents the solar X-ray flux distribution from 12 to 18 May as observed by GOES 12. CME erupted from the active region of the Sun for several hours with solar wind speed increasing to ~900 km/s. The distribution of proton flux for these days was observed by GOES 11 at three energies ≥10 MeV, ≥50 MeV, and ≥100 MeV (Figure 1b). The protons of energy ≥10 MeV were accelerated throughout a large fraction of the heliosphere. During this event the proton flux ≥10 MeV increased by about three orders of magnitude on 15 May at 00:05:00 UT. A maximum deviation in the Earth's magnetic field was registered [*Dandouras et al.*, 2007]. Bright auroras were seen on Earth at high latitudes during 15 to 17 May 2005 as a result of the CME- impact on the Earth's magnetic field (website: http://spaceweather.com/aurora). The highest AE index was reported as ~2000 nT during this event. The Dst index reached −250 nT at 09:30 UT on 15 May (website: http://swdcww.kugi.kyoto-u.ac.jp/ae_provisional/200501/index_20050117.html). No direct responses to the solar X-ray flare and CME event in the form of sudden ionospheric enhancements on other planets have been observed. We have detected such effects in the ionosphere of Mars as observed by the MGS. The calculation of flare induced electron density was also carried out for the E region ionosphere of Mars using the observed X-ray flux.

[3] In this paper we have also compared the Martian ionospheric responses to the flare and CME event with the corresponding responses in the Earth's ionosphere, although GOES did not measure X-ray flux in the wavelength range 10–50 Å, which ionizes the E region of Mars [*Haider et al.*, 2002]. To confirm that this flare had consequences in the E region ionosphere, we searched the Solar and Heliospheric Observatory (SOHO) data bank. Our search showed that EUV fluxes (260–340 Å) did not enhance significantly, whereas fluxes integrated over the broad wavelength range from 1 to 500 Å (soft X-rays plus EUV) increased by 15% on 13 May. This trend has suggested a greater enhancement in the wavelength band 1 to 50 Å (soft X-rays only), which can increase the electron densities in the D- and E- region ionosphere of both Mars and Earth.

2. Effects of X-ray Flare and CME on Mars

[4] The Earth-Sun-Mars angle was nearly 52° between 12 and 18 May 2005 when the X-ray flare occurred on 13 May (website://www.windows.ucar.edu/). Figure 2 represents the measured TEC normalized to the minimum value of each respective day between 12 and 18 May 2005. Sixty two MGS profiles of electron densities were used to obtain the TEC in the E region ionosphere of Mars. The E layer peak sometimes appears as a shoulder and sometimes as a clear peak. 50 electron density profiles out of these data sets have clear peaks, 10 profiles presented peak at altitudes 107 to 109 km, 24 profiles at altitudes 110 to 114 km and 16 profiles at altitudes 115 to 120 km. These profiles were integrated from their minimum to peak altitudes. 12 of the electron density profiles did not show clear E layer peaks. We have integrated these profiles from their lower altitude to 120 km. All the profiles were observed at nearly the same latitudes (65.3°–65.6°N), the same solar zenith angles (82.4°–83.5°) and the same local time (14.4–14.5 LT) on Mars but they

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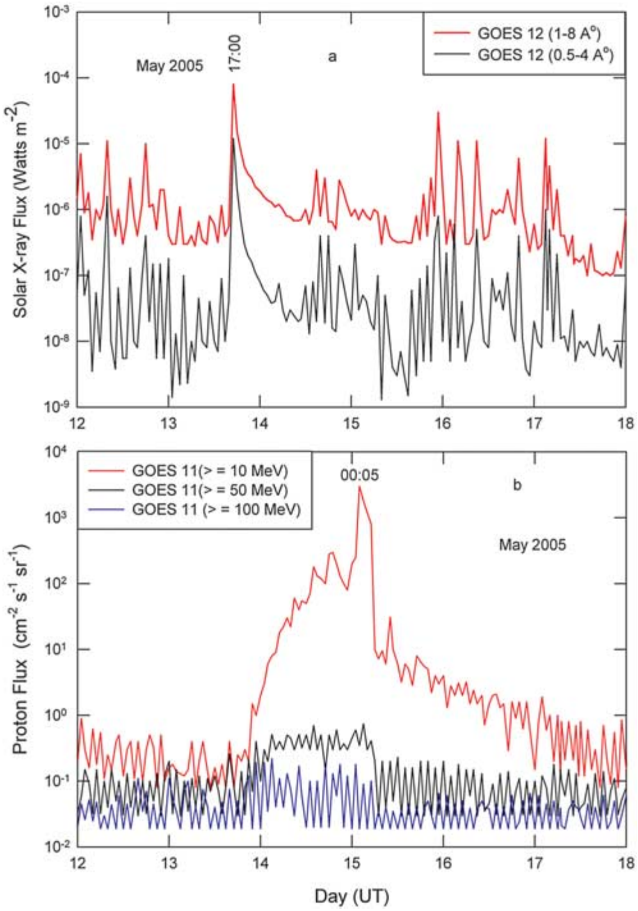

Figure 1. (a) Solar X-ray flux distributions between 12 and 18 May 2005 measured by GOES 12 spacecraft at Earth for two wave length bands: XS (0.5 to 4 Å), solid black line, and XL (1 to 8 Å), solid red line. (b) Proton flux distribution between 12 and 18 May 2005 measured by GOES 11 spacecraft at Earth for three energies: $\geq$10 MeV (red color), $\geq$50 MeV (black color), and $\geq$100 MeV (blue color).

corresponded to different longitudes [*Hinson et al.*, 1999]. About 3% error is found in these observations. Day-to day and longitudinal variabilities in the E layer peak are about 5%. There was no abrupt change in the ionosphere of Mars on 12 May before the event occurring on the 13 May. The TEC was calculated using the observed peak X-ray flux of 13 May at 17:00 UT by applying our method previously described [*Haider et al.*, 2002].

[5] The Sun's photon and particle radiations reach Earth's ionosphere in about 8 min and a few days respectively, so that any sudden changes in them should mark their effect on Earth with corresponding time delays. Since the mean distance of Mars from Sun is 1.52 AU the solar flux arrives at Mars with a time delay of $\sim$4–5 min with respect to Earth. Thus the peak X-ray flux at 17:00 UT (as observed on GOES 12) on 13 May in Figure 1a must have reached Mars $\sim$4 min later, that is, at 17:04 UT. MGS has observed the electron density a few hours before and after this solar flare. Before the solar flare the ionosphere of Mars was calm on 12 and 13 May. Just after the solar flare a very large increase in the TEC may be noted in Figure 2. The relative E region TEC increased by a factor of $\sim$10 at its peak at 17:11:00 UT. The peak electron density N_m was determined by assuming balance between the production rate (q_m) and the loss rate (α N_m^2) at E peak altitude according to the relation, $\alpha N_m^2 = q_m = (\eta S/eH) \cos\chi$, where α is the recombination coefficient, S is the solar ionizing flux at the top of the atmosphere, η is the ionization efficiency, H is the atmospheric scale height, χ is the solar zenith angle, and e = 2.718. If there are no changes in η, H, α, and χ then N_m as well as its altitude should remain unchanged. Under this condition relative increase in electron density can be represented as $N_m^f/N_m = (S^f/S)^{0.5}$, where S^f and N_m^f are the solar flare's ionizing flux and flare induced electron density respectively. By putting the values of solar flare flux S^f as $\sim 1 \times 10^{-4}$ Watts/m^2 and mean solar flux S as $\sim 1 \times 10^{-6}$ Watts/m^2 from Figure 1a, we get an expected increase in electron density by factors of $\sim$10. During the long duration the Sun was active the effect of the X-ray flare remained in the E region ionosphere of Mars for about an hour. The resulting TEC increase as observed was by a factor of 6 at 18:07:13 UT on 13 May (Figure 2).

[6] The solar wind near Mars interacts directly with the ionosphere, which acts as an obstacle and diverts the solar wind around it [*Acuna et al.*, 1998]. Actually it is a magnetic barrier, which diverts the bulk of solar wind shock around the planet. There exists a sharp boundary (ionopause) between the magnetized magnetosheath and ionosphere. The locations of magnetosheath and ionopause can change with the solar wind dynamic pressure. Thermal pressure balances magnetic pressure at the ionopause boundary. Mass loading of the magnetosheath flow does affect the flow behind the shock such that the pick up of the neutral ionized outside the ionopause contributes to the further stagnation of the flow and to the growth of the magnetic barrier and consequently also contributes to the development of the magnetotail. MGS has observed the magnetosheath at about 435 km on the sunlit hemisphere of Mars during quiet conditions [*Mitchell et al.*, 2000]. In the magnetosheath, the planetary neutrals

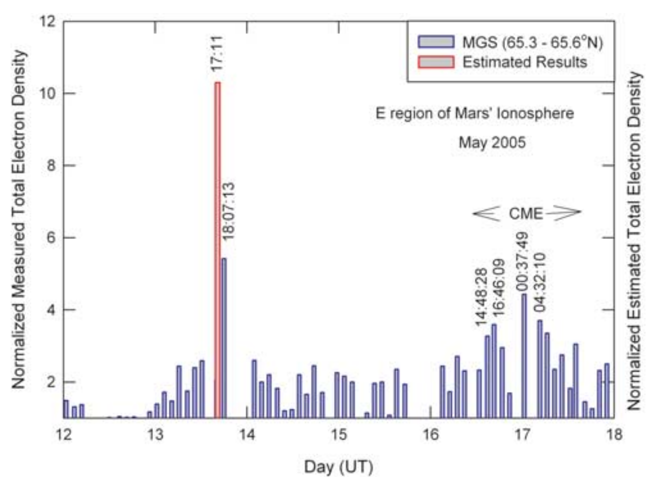

Figure 2. Normalized measured TEC distribution between 12 and 18 May 2005 measured by the MGS radio occultation experiment in the E region ionosphere of Mars at latitude 65.3°–65.6°N are shown by the blue color. Normalized estimated TEC is represented by the red color. CME arrival and its effect at 14:48:28 UT, at 16:46:09 UT on 16 May, and at 00:37:49 and 04:32:10 UT on 17 May at Mars are marked by an arrow line.

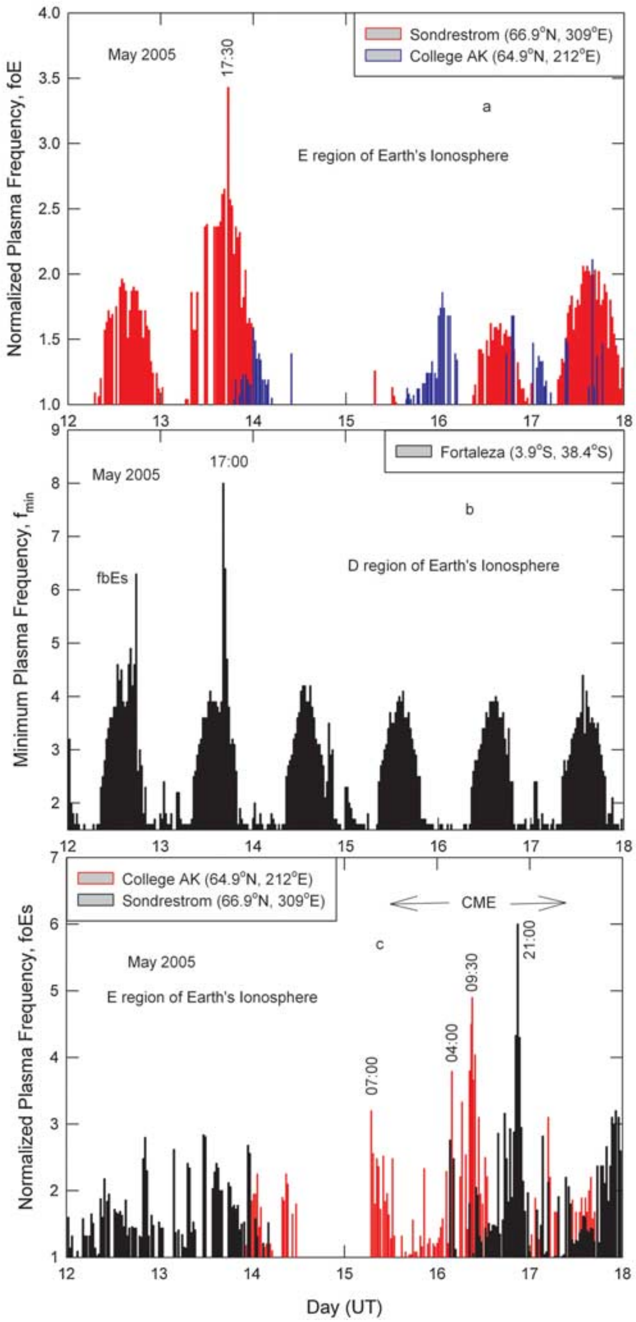

Figure 3. (a) Normalized plasma frequency, foE, distribution between 12 and 18 May 2005. Red and blue colors represent the observations made by ionosondes at Sondrestrom (66.9°N, 309°E) and College, AK (64.9°N, 212°E), respectively, in the E region ionosphere of the Earth. (b) Minimum plasma frequency, f_{min}, reflected by the F layer indicative of D region ionization over Fortaleza observatory (3.9°S, 38.4°S) during 12 to 18 May 2005. The blanketing frequency of sporadic E layer probably due to wind shears at low latitude is marked as fbEs near18:30 UT on May 12. (c) Normalized sporadic plasma frequency, foEs, distribution between 12 and 18 May 2005. Red and black colors represent the observations made by ionosonde at College, AK (64.9°N, 212°E), and Sondrestrom (66.9°N, 309°E), respectively, in the E region ionosphere of Earth. The effects of CME arrival are marked by arrow line between 15 and 16 May.

are mainly H atoms of the hydrogen corona. In this region the fast hydrogen atoms are produced by charge exchange between solar wind protons and hydrogen corona. These energetic proton-hydrogen atoms have the same energy as the solar wind protons, and move in the same direction as that of the fast protons just before the collisions [*Haider et al.*, 2002]. In this way the magnetosheath of Mars can be compressed similar to that observed in the Earth's magnetosphere [*Dandouras et al.*, 2007] and the accelerated solar wind protons turned into fast hydrogen atoms at lower altitude. Thus, the shock proton-hydrogen atoms of high flux driven by CME can penetrate deep into the Martian atmosphere and loose their energy into the E region ionosphere. As a result, TEC increased suddenly by factors of 3.5 to 4.5 between 16 and 17 May at 14:48:28 UT, 16:46:09 UT, 00:37:49 UT and 04:32:10 UT (Figure 2). The relaxation phase of the areomagnetic storm was registered on 17 May after 14:21:15 UT in four remaining profiles with relatively weak enhancements in TEC by factors of ~1.2 to 2.2. This suggests that the CME cloud reached Mars ~38 hours after it encountered the GOES and pounded the E region ionosphere of Mars with a powerful solar storm. There were two spacecrafts, Mars Express and MGS measuring the Martian plasma environment during the period of 12–18 May 2005. The Ion Mass Analyzer (IMA) on board the Mars Express, to measure the characteristics of solar wind [*Barabash et al.*, 2007], was off during this period, therefore, we do not have information from Mars Express about the solar wind at the time of associated shock arrivals on Mars. MGS does not carry an experiment to observe the velocity and flux of solar wind protons on Mars but it has a magnetometer, whose data can be used to derive indirectly information about the solar wind pressure. A notable increase of the magnetic field component perpendicular to the surface of Mars can be seen in this data during 12–18 May 2005 at ~420 km [*Crider et al.*, 2005]. The maximum value of the corresponding magnetic pressure is about 11 nPa, which is about a magnitude larger than the mean pressure (1.36 nPa) and median pressure (0.95 nPa) in 2005. Therefore, these measurements provide an indirect evidence of the arrival of CME at Mars during 12 to 18 May 2005.

3. Effects of X-ray Flare and CME on Earth

[7] To determine the consequences of this flare on Earth, we searched measurements made by ionosondes in the E region ionosphere at nearly the same latitude as on Mars as well as at some low latitudes stations. This instrument transmits frequencies in the 1-to 30 MHz range and records the time delay of echoes reflected from the ionosphere [*Reinisch et al.*, 2004]. There are three ionosonde stations viz. Zhigansk (66.8°N, 123.4°E), Sondrestrom (66.9°N, 309°E) and College, AK (64.9°N, 212°E), which are situated at nearly the same high latitude region as that of the MGS observing locations on Mars. The flare of 13 May was so severe that the ionosonde at Zhigansk was under black out for several hours. Continuous datasets available at Sondrestrom and College, AK, available at 30 min resolution were used in this study [*Reinisch et al.*, 2004]. About 5–10% uncertainty was found in these measurements. In Figure 3a we have plotted the E layer plasma frequency, foE normalized to its minimum value on each respective day between 12 and 18 May 2005.

The normalized sporadic E layer plasma frequency, foEs, is shown in Figure 3c for these days. The ionosonde at Sondrestrom measured an increase by a factor of ~3.5 in foE at 17:30 UT just after the solar flare. During the pre and post flare period the foE appeared to be higher than might be expected. The precise cause is not known to us. In any case the major signature of the 13 May flare on Earth was a large enhancement in the E layer peak density. Because the E layer is ionized by both EUV and soft X-rays and the EUV flux did not change during these flares, the Sondrestrom results must indicate enhanced ionization by soft X-rays. This confirms that the estimated TEC enhancements are produced in the E region ionosphere of Mars due to a typical flare spectrum of greater relative flux increase at shorter wavelengths. We report that the X-ray flare of 13 May produced concurrent enhancements in the ionospheres of Earth and Mars. The relative increase in the E region ionosphere of Mars at 17:11 UT and 18:07:13 UT are consistent with the enhancement at its corresponding site on Earth. GOES X-rays were enhanced by an order of magnitude during this flare. They were sufficiently energetic to penetrate to an altitude around 60 km or less on both Mars and Earth. MGS measurements of electron density at such heights over Mars are not available.

[8] Ionosondes can not directly measure the electron density in the D region ionosphere of Earth but its presence can be inferred from the radio wave absorption indicated by the minimum frequency, f_{min} reflected by upper layers. Figure 3b shows the variation of the f_{min} as registered by the ionosonde at Fortaleza observatory (3.9°S, 38.4°W). The large increase of the f_{min} that can be noted at 17 UT on 13 May is a clear indication of the large enhancement in the D region electron density that was responsible for the total absorption of up-going radio waves at frequencies below 8 MHz. Therefore, while no data was available around this altitude in the ionosphere of Mars, the ionosonde Earth observations do show D region enhancement for this event. The results over Fortaleza show that there was significant enhancement in energetic X-rays which penetrated to an altitude around 60 km and caused significant radio wave absorption as indicated by the f_{min} increase.

[9] A large geomagnetic storm occurred on 15 May. During this event the interplanetary magnetic field was directed southward. Very high energy particles ejected by the Sun were detected simultaneously in the solar wind by the Cluster and in the magnetosheath by the Double star spacecrafts [*Dandouras et al.*, 2007]. The measurements showed that the CME reached Earth in a few hours and influenced the ionosphere with a powerful solar storm. This effect was recorded by an increase in sporadic E layer plasma frequency on 15 and 16 May as measured by ionosondes at College, AK, and Sondrestrom. At College, AK, the values of relative foEs were enhanced on 15 May by factors of 3.2 at 07:00 UT and on 16 May by factors of 3.8 and 4.9 at 04:00 UT and 09:30 UT respectively. Later, greater enhancement in foEs was observed by a factor of 6 at Sondrestrom on 16 May at 21:00 UT. At high latitude, Es layer formation by the wind shear mechanism is relatively inefficient as compared to the midlatitude region, where metallic ions of Fe^+ and Mg^+ have recombination rates smaller than for molecular ions and remain charged long enough to be pooled together into highly dense thin sheets of increased ionization level nearly twice more intense than normal E layer. We note that relative ionization indicated by foEs at 07:00 UT, 04:00 UT, 09:30 UT and 21:00 UT represents increases by factors of 3 to 6, which are significantly higher than that is expected by wind shear mechanism. Such an increase in foEs can be attributed to ionization by energetic particles associated with the storm. We, therefore, report that these relative enhancements in foEs are associated with geomagnetic disturbances which move the auroral oval to the high mid-latitude region during an intense geomagnetic storm. The relative increases in foEs on 15 May at 07:00 UT and 16 May at 04:00 UT, 09:30 UT and 21:00 UT in the E region of Earth's ionosphere are consistent with the enhancements of TEC on 16 May at 14:48:28 UT and 16:46:09 UT and 17 May at 00:37:49 UT and 04:32:10 UT seen in the Mars' ionosphere. There was a significant delay in the effects observed on Mars as compared to that on Earth.

4. Discussion and Conclusion

[10] We report that the physical processes of magnetic storms are different on Earth and Mars. During a magnetic storm shock waves driven by CME compress the Earth's magnetosphere leading to increased energetic particle precipitation into the ionosphere that leads to auroras and sudden increase in the electron density. The electron density increase in the present event was observed between 7 to 45 hours after the detection of the CME by GOES 11. We have traced the shock-triggered events from Earth, where auroral storms were recorded between 15 and 16 May 2005. The large increases in foEs on these days were clear indications of such auroral storms. They were produced by energetic particle precipitation in the auroral oval extending to lower latitudes. The auroral storm effects on Mars have quiet different characteristics. Mars has no strong remnant of an ancient intrinsic magnetic field in the northern hemisphere [*Acuna et al.*, 1998], so Venus-like diffuse aurora could exist in the northern hemisphere of Mars [*Fox*, 1992] during such events. It is possible that the interplanetary shocks may have compressed the magnetosheath of Mars during this violent solar eruption event. The solar wind protons then interacted with the hydrogen atoms of the compressed magnetosheath. This interaction involving charge exchange process yields energetic hydrogen atoms that precipitate down into the lower atmosphere with the same speed as shock protons before collision [cf. *Haider et al.*, 2002] and deposit their energy into the E region ionosphere of Mars after impact with the atmospheric gases. The ionization produced by this process resulted in the increase of the TEC in the E region that was apparently observed by the MGS starting from around 15 UT on 16 May. This is about 30 hours after the first observation of the storm effect on Earth. The effect on Mars appears to have lasted for about one day, which is shorter than the duration of the corresponding effects on Earth. Thus we note that a different and unusual source of ionization is active in the E region ionosphere of Mars. This establishes that shocks retain their ability to alter the low altitude ionosphere of Mars as well as the Earth's ionosphere.

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